LLNL-JRNL-482133

Using pre initiation by sub-ns laser pulses to enhance optics mitigation

C. W. Carr, D. A. Cross, M. A. Norton, R. A. Negres

May 2, 2011

Optics Express

Disclaimer

Using pre initiation by sub-ns laser pulses to enhance optics mitigation

C.W. Carr, D. A. Cross, M. A. Norton, R. A. Negres
Lawrence Livermore National Laboratory, Livermore, CA 94551

Abstract: Growth of laser damage on SiO_2 optical components used in high power lasers can be reduced or eliminated by pre-exposure to pulses of a few hundred ps in duration. Such pre-exposure would cause weak locations on the optics surface to self-identify by initiating very small damage sites. The sites which initiate will be only a few microns in diameter and will have a very low probability of growing even without any further treatment. Repairing damage sites when small is important because both laser mitigation and acid etching have a near perfect ability to prevent such small sites from growing.

References and links

1. Prasad, R.R., et al., "*Design of a production process to enhance optical performance of 3 omega optics,"* Proc. SPIE **5273**, 296 (2003)
2. Prasad, R.R., et al., "*Enhanced performance of large of optics using UV and IR lasers,"* Proc. SPIE **5273**, 288 (2003)
3. Bertussi, B., et al., *Initiation of laser-induced damage sites in fused silica optical components.* Optics Express, 2009. **17**(14): p. 11469-11479.
4. Stolz, C.J., et al., *Laser damage initiation and growth of antireflection coated S-FAP crystal surfaces prepared by pitch lap and magnetorheological finishing, SPIE* **5991**, L9911 (2005)
5. Bercegol, H., et al., *Progress in the understanding of fracture related laser damage of fused silica Proc. SPIE* **6720**, 72003 (2007)
6. Negres, R.A., et al., *Growth behavior of laser-induced damage on fused silica optics under UV, ns laser irradiation.* Optics Express, 2010. **18**(19): p. 19966-19976.
7. Guss, G., et al., *High-resolution 3-D imaging of surface damage sites in fused silica with optical coherence tomography, Proc. SPIE* **6720**, F7201 (2008)
8. Suratwala, T., et al., *HF-Based Etching Processes for Improving Laser Damage Resistance of Fused Silica Optical Surfaces.* Journal of Amarican Ceramics Society **94**(2), 416 (2011)
9. Adams, J.J., et al., *Pulse length dependence of laser conditioning and bulk damage in KD2PO4.* Proc. SPIE **564**, 265 (2005)
10. Negres, R.A., P. DeMange, and S.G. Demos, *Investigation of laser annealing parameters for optimal laser-damage performance in deuterated potassium dihydrogen phosphate.* Optics Letters, 2005. **30**(20): p. 2766-2768.
11. Carr, C.W., J.B. Trenholme, and M.L. Spaeth, *Effect of temporal pulse shape on optical damage.* Applied Physics Letters, **90**(4), 041110 (2007)
12. Carr, C.W., et al., *The effect of laser pulse duration on laser-induced damage in KDP and SiO2,* Proc. SPIE **6403**,K4030 (2007)

13. Carr, C.W., H.B. Radousky, and S.G. Demos, "*Wavelength dependence of laser-induced damage: Determining the damage initiation mechanisms,"* Physical Review Letters, **91**(12), 127402 (2003)
14. Estler, R.C. and N.S. Nogar, *Chemical Precursor to Optical-Damage Detected by Laser Ionization Mass-Spectrometry.* Applied Physics Letters, **52**, 2205 (1988)
15. Natoli, J.Y., et al., *A quantitative study of laser damage probabilities in silica and calibrated liquids: Comparison with theoretical prediction.* Proc. SPIE**4347**, 295 (2001)
16. Trenholme, J.B., M.D. Feit, and A.M. Rubenchik, "*Size-selection initiation model extended to include shape and random factors,"* Proc. SPIE **5991**, X9910 (2005)
17. Miller, P.E., et al. "*Fracture-induced subbandgap absorption as a precursor to optical damage on fused silica surfaces,"* Optics Letters, **35**, 2702 (2010)
18. Carr, C.W., J.D. Bude, and P. DeMange, "*Laser-supported solid-state absorption frons in silica,"* Physical Review B, **82**, 184304 (2010)
19. Carr, C.W. and J.M. Auerbach, "*Effect of multiple wavelengths on laser-induced damage in KH(2-x)DxPO4 crystals,"* Optics Letters, **31**, 595 (2006)
20. Nostrand, M.C., et al. "A large aperture, high energy laser system for optics and optical component testing" , Proc. SPIE **5273**, 2003
21. Bertussi, B., et al. "*SOCRATE: an optical bench dedicated to the understanding and improvement of a laser conditioning process,"* App. Optics, **45**, 8506 (2006)
22. Lindl, J.D., et al., "*The physics basis for ignition using indirect-drive targets on the National Ignition Facility,"* Physics of Plasmas, 2004. **11**(2): p. 339-491.
23. Stuart, B.C., et al., "*Nanosecond-to-femtosecond laser-induced breakdown in dielectrics,"* Physical Review B, 1996. **53**(4): p. 1749-1761.
24. Cross, D.A. and C.W. Carr. "Analysis of 1ω Bulk Laser Damage in KDP" submitted to Applied Optics *(2011)*
25. Lamaignere, L., et al., "*Parametric study of laser-induced surface damage density measurements: Toward reproducibility,"* J. Applied Physics **107**(2) (2010)
26. Carr, C.W., et al., "*Techniques for qualitative and quantitative measurement of aspects of laser-induced damage important for laser beam propagation.* Measurement Science & Technology," 2006. **17**(7): p. 1958-1962.
27. Hooker, C.J., et al., "*Pulse-Length Scaling of Laser Damage at 249 Nm in Oxide and Fluoride Multilayer Coatings,"* Optics Letters, 1993. **18**(12): p. 944-946.
28. C.W. Carr & P. Demange. "Effect of pulse shape on damage iniation in SiO2" In preperation for Optics Express
29. Carr, C.W., et al., "*Complex morphology of laser-induced bulk damage in K2H(2-x)DxPO4 crystals,"* Applied Physics Letters, 2006. **89**(13)
30. R. A. Negres et al., "*Size dependence of the probability of growth for small damage sites"*, Submitted to Applied Optics

***I*. Introduction**

The output of both large-aperture and table top lasers is often constrained by the need to avoid inducing damage in the laser's optics. This is particularly true in the case of Fusion class lasers such as the National Ignition Facility (NIF) in the

United States and the Laser Mega-Joule (LMJ) in France. In the past a number of efforts have been made to reduce laser induced damage on the exit surface of SiO_2 optics by pre-initiating damage and then repairing it as a final processing step before the optics are used [1-3]. This method has the advantage of allowing weak locations on the surface of the optic to self-identify by initiating damage under controlled circumstances. Because the process is done before installation, the localized damage on the optic can be repaired after a single initiation pulse, rather than after being initiated and grown for some number of shots as would likely be the case if the damage were to initiate after installation [4-6]. Off-line pre-initiation reduces the logistical burden of a large laser facility by reducing the number of times optics must be installed and removed from the system. This strategy would be significantly enhanced if sites can be initiated small enough to ease repair [1-3, 7, 8]. It should be noted that pre-initiation is a distinctly different procedure than conditioning, though the terms are occasionally used interchangeably. The term conditioning has historically been used to describe a stepwise increase in laser irradiation which makes a material or component more resistant to laser-induced damage without actually producing observable damage and therefore eliminating the need for repair. For example, laser conditioning is routinely employed to increase the bulk damage threshold of KDP and DKDP materials for frequency harmonic generation [9, 10].

Past pre-initiation work has utilized XeF lasers because of their excellent beam quality and reliability (see for example the work by Prasad et al or Bertussi et al). The disadvantage to using a XeF laser is that the pulse shape has an effective temporal duration much longer than the pulses used on Fusion class laser systems [11]. The duration of the single-pass XeF pulses could be described as ~9 ns with a Full Width at Half Maximum (FWHM) measure, or as ~16 ns, or even 30 ns in duration for $1/e^2$ and $1/e^3$ measurements, respectively. Though the effects of pulse duration have been explored previously [12] we will elucidate here that the pulse shape (and hence duration) is relevant to the pre-initiation process in two ways. Laser induced damage in the ns regime has been shown to be comprised of a quick series of events starting with an initial energy absorption by an extrinsic precursor [3, 13-17]. After the initial first few hundred picoseconds laser energy is deposited on a temperature activated absorption front in the bulk silica [18]. Because the mechanisms for the initial energy deposition are different from those governing the final damage site size [19], it is not surprising that different measures of the pulse are more relevant when discussing initiation density (or probability) and size of initiated damage sites [11]. In this work we show that the temporal characteristics of a laser pulse are equally, if not more important parameters than spatial laser parameters to achieve controlled pre-initiation of SiO_2 optics.

II.a Damage initiation

The Optical Sciences Laser (OSL) Facility at Lawrence Livermore National Laboratory (LLNL) was used to perform the SiO_2 surface damage testing experiments [20]. The OSL laser can produce laser pulses of near arbitrary temporal shape with durations up to 30 ns and is used in these experiments to initiate damage on the exit surface of SiO_2 optics with pulses of Gaussian shape with different FWHM as well as more complex pulse shapes, similar to those output from an XeF laser system and to those used for early ignition experiments on the NIF [20-22] (see Fig. 1 inset). The techniques used to generate and analyze damage testing data were reported elsewhere [23]. In brief, samples are contained in a vacuum chamber with a pressure of 10^{-5} torr at room temperature. Spatially separated sub-apertures on the same test sample are sequentially exposed to a single pulse. In this way multiple pulse shapes can be tested on a single sample to reduce any effect sample variability may have on the measurements. Similarly, the spatial contrast in the test beam enables a single sub-aperture to be tested with one pulse shape with a range of laser fluences. The local density of damage sites are measured with an automated microscope and correlated to the local fluence. The relationship between laser fluence and damage density is typically referred to as a $\rho(\phi)$ or “rho of phi” measurement or curve. Figure 1 shows two example $\rho(\phi)$ curves.

II.b The effect of Pulse Shape on Damage Initiation density

Though the focus of this work is the effect of pulse shape and duration on the size at which damage sites initiate and the implications to subsequent repair, a brief discussion on the effects of pulse shape on the number of sites initiated is warranted to put this work in context. The effect of pulse duration in the ns regime on the propensity of damage initiation is well known and is often described by pulse scaling for both density and probabilistic measurements [24, 23]. Equation 1 demonstrates the use of pulse scaling to damage density measurements.

$$\rho_2(\varphi;\tau_2) = \rho_1\left(\varphi \times \left(\tau_1/\tau_2\right)^{\gamma};\tau_1\right) \tag{1}$$

where ρ_1, ρ_2, τ_1, and τ_2 are the densities of damage sites produced by two pulses of the same fluence with durations of τ_1 and τ_2, respectively. The parameter γ is the power or pulse scaling coefficient. A number of publications have proposed meaning for γ, however the practical implication is that a large power of γ indicates a material that is highly sensitive to pulse duration, while a lower value of γ occurs when a material's propensity to damage is less sensitive to different pulse durations [11,12, 24,25].

To illustrate the effect of pulse duration (and shape) on damage initiation, $\rho(\phi)$ curves for pulse shapes typical for XeF lasers as well as one similar to a proposed pulse for use in inertial confinement fusion experiments are shown in Figure 1. The data show that the fluence of the XeF pulse must be 170% that of the ignition-like pulse in order to achieve the same damage density. More detailed examinations of the effects of pulse shape on the density of damage sites are available elsewhere [12,28].

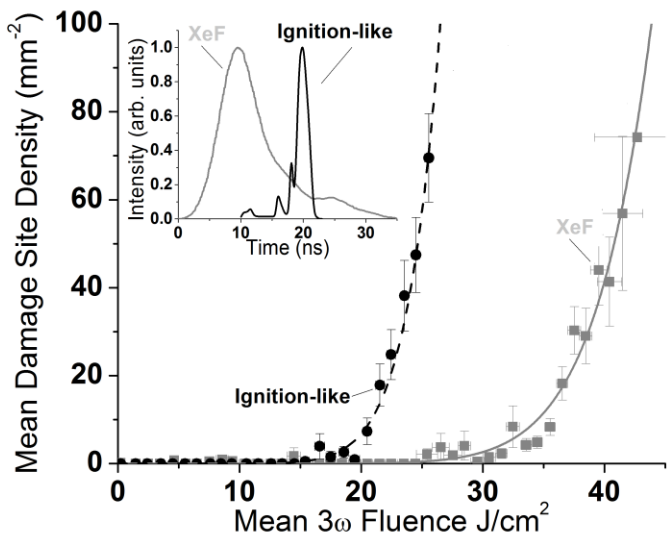

Fig. 1: Measured damage density as a function of fluence from the XeF (solid squares) and ignition-like pulse shapes (solid circles), respectively. The inset shows XeF and ignition-like temporal pulse shapes. The solid and dashed lines are included as guides to the eye for the XeF and Ignition-like data, respectively.

III. The effect of pulse duration on damage site initiation size

After the damage was initiated the samples were then coated with a few mono-layers of Au (for enhanced conductivity) before the acquisition of SEM images of individual damage sites. Figures 2(a) and 2(b) show damage sites initiated on the exit surface of SiO_2 optics with Gaussian shaped pulses of various lengths and one site initiated with a XeF pulse, respectively. All damage sites are from regions with damage densities of ~10 sites per mm^2. Damage sites produced by the ignition-like pulse are indistinguishable to those produced by a 3 ns Gaussian pulse.

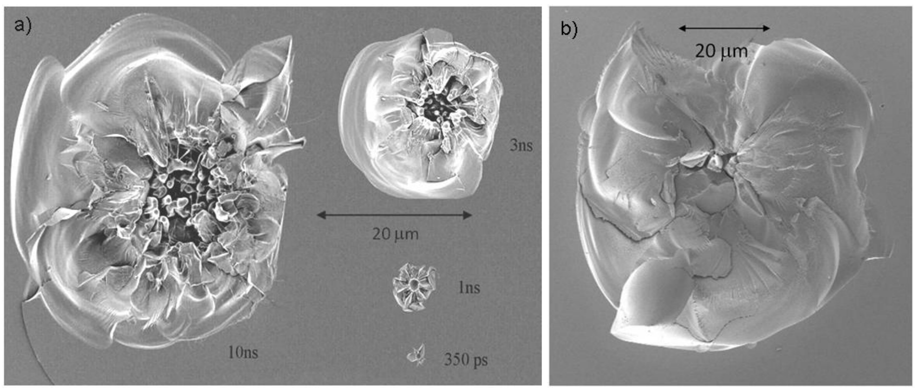

Fig 2. SEM images of damage sites produced on the exit surface of SiO_2 optics using (a) Gaussian pulses of various durations and (b) XeF pulse as shown in the inset of Fig. 1.

By comparison damage sites produced by a typical pulse shape from a XeF laser are 4 times larger than those produced by a 3 ns pulse and more than 20 times larger than sites produced by a 350 ps pulse. Similar pulse duration dependence to damage site size has been previously reported for bulk sites in KDP crystals [29]. It should be noted that because sites were chosen from regions with similar densities of sites, the fluence which created each site is necessarily different from one another. The fluence used to create the XeF sites (~35 J/cm^2) is 1.7 times higher than that needed for the 3 ns Gaussian pulse and 8 times higher than that needed for the 350 ps sites.

IV. Effect of site size on damage growth

Measurements of the probability that a damage site will grow under subsequent laser exposure as a function of size (see Fig. 3) show that the smaller the site is the smaller the likelihood of growth on a given shot [30]. This observation and the above discussed dependence of initiation size on pulse duration raises the intriguing possibility of initiating damage sites small enough that they will by very unlikely to grow. Pulses as short as a few tens of ps (or shorter) will produce sites as small as a micron or less. Even a site initiated with 500-ps pules will have a probability of growth of 10^{-4}.

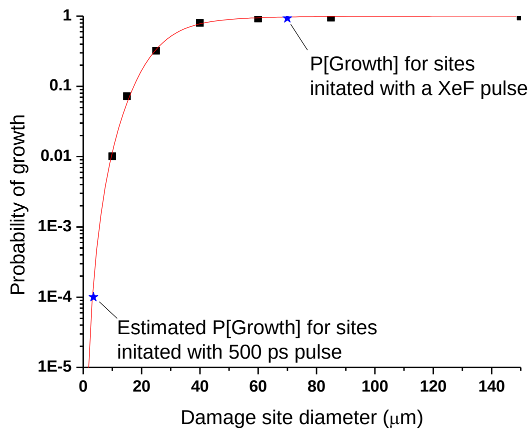

Fig 3. Measured probability of a damage site to grow with 5 ns flat-in-time pulses with a fluence of 9 J/cm^2 as a function of site size (black squares) and estimated (blue stars) for the 3.5 micron and 70 micron sites typical of initiation with 500 ps and XeF laser pulses, respectively. The red line is a logistic fit to the measured probability data.

V. Summary

In this work we have verified that the effects of pulse shape on initiation density previously reported for bulk damage in KDP are also present on exit surface SiO_2. In addition to the effects on the density of initiations we show that the duration of the pulse strongly affects the size at which damage sites initiate. Size is important both because of the previously reported effects on the success of optics repair, but also because small sites are less likely to grow, even without repair. These findings are immediately applicable to optics preparation for fusion class lasers. By replacing the traditional XeF type systems, historically used for pre-initiation and conditioning, with lasers with shorter pulse durations damage sites can be initiated with a much smaller initial size, reaping the benefits associated with smaller sites mentioned above. In addition, as shown in the present work, by using short enough laser pulse durations to pre initiate sites there is the possibility of producing sites so small that they do not grow at all under exposure to laser conditions typical to fusion class laser systems.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.